Tidal Turbine-Fish Interaction Pilot Study in the Aquatron Controlled Lab Space

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Abstract*—To date there are limited laboratory studies on the interaction of marine life with marine renewable energy devices. The Aquatron Laboratory at Dalhousie University is designed to study marine life in a controlled marine lab environment. The 15.24 m diameter pool tank is equipped with four 75-HP circulation pumps that can generate tidal currents up to 2.4 m/s velocities using ocean water. The process for modifying the facility to study the impact of hydrokinetic turbines on fish is presented. The installation of a 0.9 m diameter 3-blade vertical axis turbine is described. The performance of the turbine is first validated against previous towing tank experiments at NRC St. John's. Tests were then performed for 3 weeks to monitor the behaviour of the turbine on Striped Bass (*Morone saxatilis*). The test protocol provided flow in the tank at 2 m/s continuously for 3 weeks with the turbine rotor locked during the first week, the rotor rotating at a tip speed ratio of 1.5 in the second week, and the rotor locked again in the third week. The intent of this study is to demonstrate the feasibility of using the Aquatron facility for turbine-fish interaction studies. The test protocol was kept relatively simple for this test series. Fifty Striped Bass varying in age from 2 to 3 years were used for these tests. The turbine had a cage around the frame to prevent fish strikes in this first phase of tests. There was a second net placed across the centre of the tank to train the fish to pass by the turbine rotor to access food on the other side of the tank as fish passage behavior near the turbine is of prime importance. Fish behaviour was monitored by counting fish passage as they swam to specific locations in the tank. Fish velocity, location, and general observations were recorded. Results presented should not be considered as definitive fish behaviour when encountering an operational turbine.

***Keywords*— Hydrokinetic, Fish, Striped Bass, Controlled Lab, Interaction.**

Fig. 1 Tidal turbine and fish study experimental setup

I. INTRODUCTION

The goal of this project was to show that the Aquatron Pool Tank at Dalhousie University, the largest ocean research facility in Canada and traditionally a marine biology facility [1], could be used to test the interaction of turbines with animals (Fig. 1). Owing to the logistical difficulty of assessing fish behaviour around tidal turbines in the environment, controlled test facilities are essential in understanding potential stressors that may influence fish behaviour and biology. As a pilot study, it was not expected that the animal behaviour would be definitive but that the results would indicate whether it would be worthwhile pursuing further testing in this facility. This paper presents Phase 1, which is the technical engineering work that was done to show that a turbine tested in the Aquatron Pool Tank could produce similar results to the same turbine tested at a traditional towing tank facility. The modifications to the tank are discussed and the physical setup for the fish–turbine interaction experiments are described. The data from the turbine, under a range of flows, is presented and a description of the experiments is included. Once the flow was verified the turbine was installed and made operational for the fish behavioural study.

Fig. 2 Free swimming Striped Bass (*Morone saxatilis*)

There are many concerns when assessing the interaction of animals with a dynamic device such as rotating blades of a tidal turbine including collision and noise [2]. The fish interaction with the turbine was designed to allow a team of researchers to observe the schooling behaviour of free swimming Striped bass (*Morone saxatilis*), shown in Fig. 2, pre-turbine operation, during turbine operation, and post- turbine operation. Schooling is a behaviour demonstrated by many freshwater and marine fish [3]. It is commonly defined as a large number of fish swimming together, all oriented in the same direction and changes to patterns can be informative on how fish schools may respond to dynamic devices in the environment.

Owing to strict rules by the animal ethics committee at Dalhousie University, the free-swimming fish had to be protected from direct impact with the blades of the turbine by putting a netting around the blades, thus not allowing the assessment of turbine collision to be made. Based on previous literature [4-6], studies showed that fish of different taxa are likely to avoid a tidal turbine and it is anticipated that future studies in the Aquatron will have the caging removed around the turbine to assess collision risk. However, the objective of this study was to observe the behaviour in the presence of a turbine in realistic flow conditions. These realistic flow conditions include changes in the noise, pressure gradients, and flow perturbations. This provided invaluable results for this pilot study to assess if this facility could be used in the future for animal/turbine interaction studies. This test facility provides a place where animals can safely be tested with experts on staff to handle them and can be used all year as it can offer temperature control. This facility is thus very valuable for the marine renewable energy industry.

II. METHODS

Following are the methodologies applied in this experiment that include: a description of the pool tank facility, the turbine testing, and the experiments involving the fish interaction with the turbine.

A. Facility

The work was carried out at Dalhousie University Aquatron Laboratory (Aquatron) in Halifax, Nova Scotia in Winter 2017. The Aquatron Pool Tank is a 15.24m diameter tank and the water depth for this test was 4m. The water exchange system allows the tank to be emptied and filled very quickly. By modifying the inflow pipe and using the large pumps to provide flow in the range of 0.6-2.4m/s, a stream of flow, similar to a flume, was pushed into and across the tank. The flow was modelled, see Fig. 3 and 4 below, and then verified by using a flow meter and an acoustic Doppler current profiler, the Nortek Vectrino Profiler.

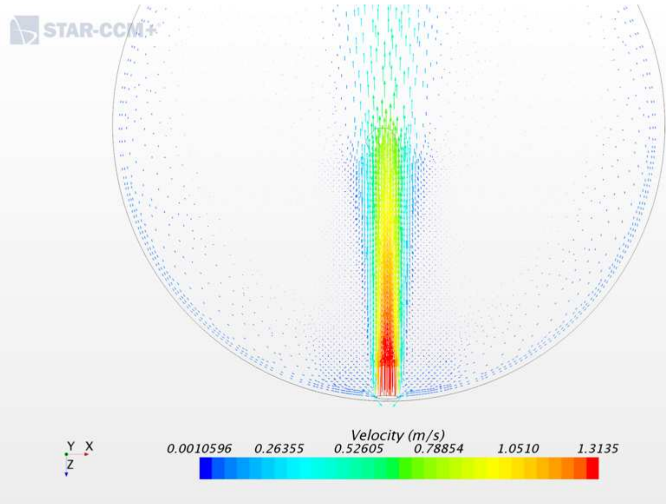


Fig. 3 Modelled Inflow to a Large Tank, Overhead View

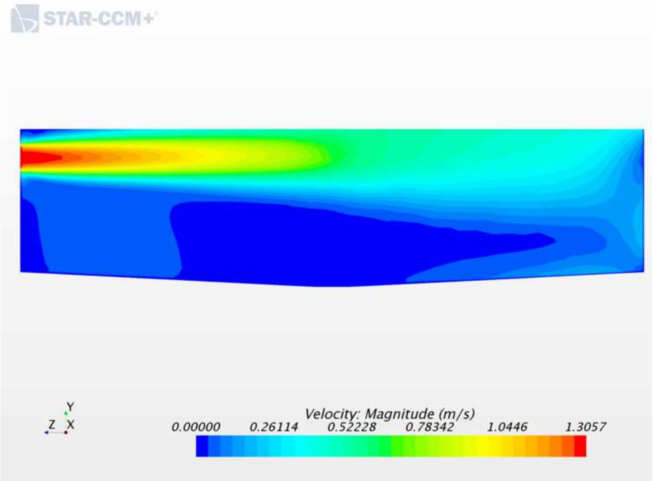


FIG. 4 MODELLED INFLOW TO A LARGE TANK, SIDE VIEW

Finally, a small turbine (~30cm in diameter) was placed in the flow and moved around the entry point of the flow to find out how the flow changed from the centre of the flow. It was determined that the flow showed consistency close to the inflow site and in a cross-sectional area that was large enough for the vertical axis turbine that was used for the tests to be tested in even flow.

B. Turbine

Quantifying the performance of the turbine involved the following sets of measurements to be obtained.

1. Quantifying the electrical losses of the permanent magnet motor. This was performed by measuring the armature resistance of the motor. This allowed the evaluation of power losses due to the electrical current driving the motor.

2. Measuring the mechanical losses as a function of angular speed of rotation. This was the mechanical loss of the motor and gearbox the motor is connected to. This dataset was collected when the turbine was disconnected from the drive shaft.

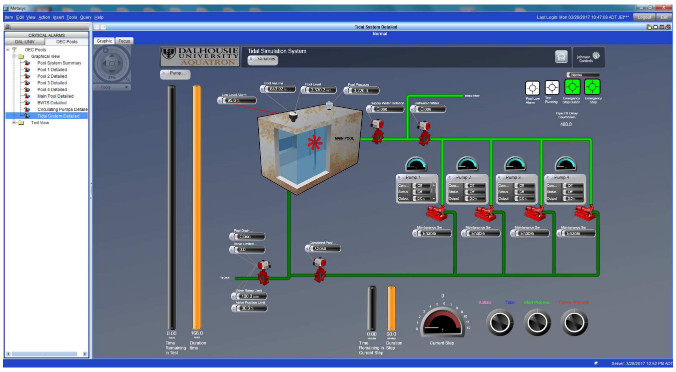
3. The motor was used to spin the turbine, with no water flow, in the same direction that the water flow would spin the turbine. The input voltage and current to the motor at various rotational speeds was measured. This dataset was used to compare the same measurements when there was water flow.

4. Collect the input voltage and current to the motor and the angular speed of the turbine at various flow rates.

5. Calculate the mechanical power of the system that was harvested by the turbine being spun for various water
6. flow rates.

The water flow rates for the data collection were 0.6, 1.2, 1.8, 2.4 m/s. The water flow rate was controlled through the water pumps at the Aquatron. The Aquatron Tidal Flow System is a web based control system that allows the user to create a powerful flume by recirculating the Pool Tank. The Pool Tank has a volume of 680 cubic meters. The water used to produce the tidal flume is drawn from the centre drain of the Pool tank into a header that feeds four 75 horsepower pumps. These pumps can produce a return current of 2.4 m/s back into the Pool Tank through a 20-inch return line that is submerged 1.5 m below the tank surface. The user can select the percentage power used by each pump and the number of pumps used to produce the flow. One pump at 100 % power produces 0.6 m/s, and each subsequent pump at 100% adds 0.6 m/s of flow to the overall speed maxing at four pumps at 100% providing a flow rate of 2.4 m/s.

The Tidal portion of the system does not produce a high or low tide in the true sense of the word within the Pool Tank, instead the program allows the user to preselect the percent power used by the preselected number of pumps at each of twelve programmable steps. The time between each of the twelve programmable steps can also be set by the operator. This allows the user to simulate changes in tidal speed over minutes, hours, or days and allows the pre-programmed cycle to continue to occur for up to a month. The control terminal for this can be observed in Fig. 5 below.



Last Login: Mon 03/20/2017 10:47:08 ADT JEt***
Low Level Alarm 95.0 %
Pool Volume 643.92 cu...
Pool Level 3,530.2 mm
Pool Pressure 3,226.3...
Supply Water Isolation Close
Untreated Water... Close
Normal
Pipe Fill Delay Countdown 480.0
Pump 1: Com... Off; Status Off; Output 0.0 %
Pump 2: Com... Off; Status Off; Output 0.0 %
Pump 3: Com... Off; Status Off; Output 0.0 %
Pump 4: Com... Off; Status Off; Output 0.0 %
Maintenance Sw Enable
Maintenance Sw Enable
Maintenance Sw Enable
Maintenance Sw Enable
Pool Drain... Close
Valve Limited... 0.0
Combined Pool... Close
Valve Ramp Limit 100.0 cpm
Valve Position Limit 30.0 %
Time Remaining in Test 0.00 hours
Duration time 168.0 hours
Time Remaining in Current Step 0.00 minutes
Duration Step 60.0 minutes
Server: 3/28/2017 12:52 PM ADT

Fig. 5 Aquatron Water Pump Terminal

In this experiment, the flow was not varied, it was fixed at 1.5 meters per/second with three pumps running at 85% percent for the duration of the study. All steps were set for the same 85% power level and the step between points was 60 minutes. The pumps ran for the duration of the study.

Voltage and current were measured from an Accuenergy AcuDC 243 DC Power and Energy Meter. The angular speed was measured from a shaft mounted encoder disk and optical sensor. These can be observed in Fig. 6 below.

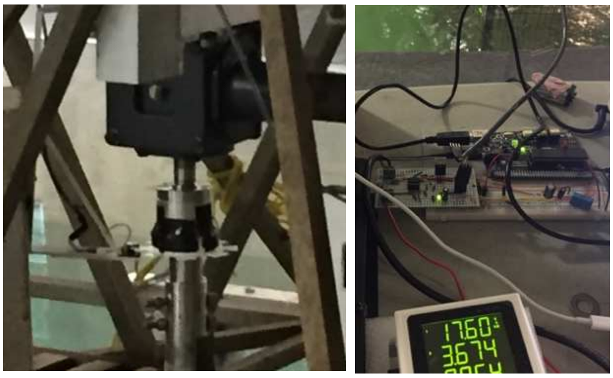


Fig. 6 Data Measurement Devices with the encode disk (left) used to determine the angular speed of the turbine and the Accuenergy meter (right) used to measure the input voltage, current and power delivered to the motor.

C. Fish

The species studied was the Atlantic striped bass (*Morone saxatilis*) as the striped bass is a specific species of interest in the Bay of Fundy, see Fig. 2. Fifty adult striped bass that were readily available at the Aquatron facility were placed in the pool via dip netting and were allowed to free swim.

To ensure that the fish swam past the turbine to feed and were seen on camera, a net was hung and weighed to the bottom of the tank as shown in Fig. 7 below. This was achieved by attaching the net to a movable bridge that the turbine was attached to. The net was hung underneath the bridge and weighed to the bottom of the tank. The net spanned the width of the tank with an opening at either end; allowing the fish to only pass through these two openings when travelling in the tank. See Fig. 6 below and Fig.1 above.

The fish behavioural study was run continuously for three weeks. The first week the flow was on and the turbine was prevented from turning. The second week the flow was on and the turbine was operating. The third week the flow was on and the turbine was again prevented from turning. This sequence was chosen to determine if the fish behaviour, post- turbine operation returned to behaviour observed pre- turbine operation.

The fish were fed with 7mm pellets, Corey Aquasea 5mm, once a day until satiation by Aquasea. The fish were fed at the same spot of the tank each day, directly under the camera. The feeding location was chosen to observe whether or not the turbine influenced the feeding behaviour of the fish. Feeding took place at different times each day to eliminate predictability and possible influence in fish behaviour.

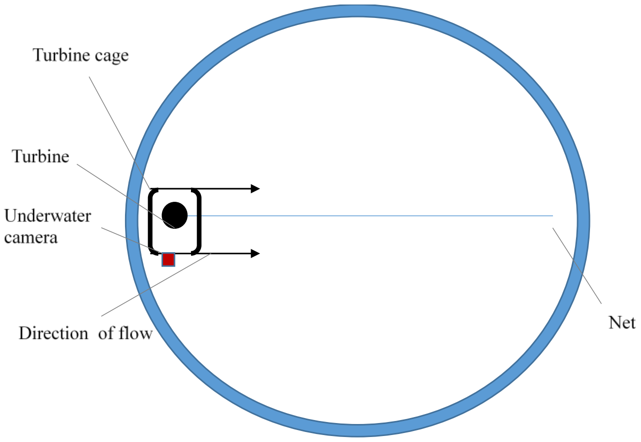


Fig. 7 Experimental Design of the experimental layout of the Aquatron pool tank, represented as the large blue circle. The blue line down the middle of the tank represents the net which is weighed to the bottom of the tank. The black box is the turbine cage with the black circle inside representing the turbine. The black arrows show the direction of the flow, and the red square shows placement of the underwater camera.

Each day, student(s) would observe the behavior of the free-swimming fish for 15 minutes under the turbine and the furthest spot from the turbine. 15 minute intervals were chosen due to available resources and by spending 15 minutes directly under the turbine and at the furthest point away, a total of 30 minutes would be observed three times a day at 8:00, 12:00, and 17:30. Behaviours noted were (i) the average time it took for the school to pass the observation window (from all the passages during the 15 minutes) and (ii) whether the fish were schooling or not. The average pass time of the school of fish was recorded by starting a time recording when the school first entered the observation window and ending the time recording when the school passed the observation window fully.

As well as the student observations, an underwater camera, Ocean Systems Splashcam Sidewinder 360, was hung in the opening between the side of the tank and the turbine, see Fig. 7 below.

Fig. 7 Fish Monitoring Camera Screenshot

The camera recorded for 6 hours a day; the maximum length of time for storage space. This added to the amount of data available for analysis in determining if there were other influences in behaviour independent of the turbine. The same behaviours recorded in the 15 minute observations were recorded and verified by the video camera recordings.

The null hypothesis that no difference in behaviour ('schooling' or 'other' behaviour) was tested from only the camera recorded data. Paired t-tests were carried out between each of the three weeks. Paired t-test were chosen since the number of data points were not consistent for each variable and the data can be considered 'paired' since the same fish were used in all three treatments. The results for each week were tested for normality with a 95% confidence interval. If normality was violated, the data was transformed, using a log transformation, to be normal. All analyses were carried out using Minitab 17.

III. RESULTS & DISCUSSION

The results of this experiment are two-fold, analysis of the turbines performance and analysis of the fish behaviour. The results and discussion will be outlined in the subsequent sections.

A. *Turbine Performance*

The power harvested by the turbine, is calculated as follows:

$$P_{no\,flow}(\omega) - [VI - I^2R - (\alpha + \beta\omega)] = P_{mech} \qquad (1)$$

Where, $P_{no\,flow}(\omega)$ is the mechanical power required to spin the turbine in water with no water flow present, V is the terminal voltage of the motor, I is the armature current of the motor, and R is the armature resistance of the motor (which was measured to be 1.45Ω), $\alpha + \beta\omega$ is the constant speed dependent friction/mechanical losses associated with the motor and gearbox assembly, and P_{mech} is the mechanical power harvested from the water flow by the turbine

The mechanical losses of the turbine assembly were measured to have the characteristic shown in Fig. 8.

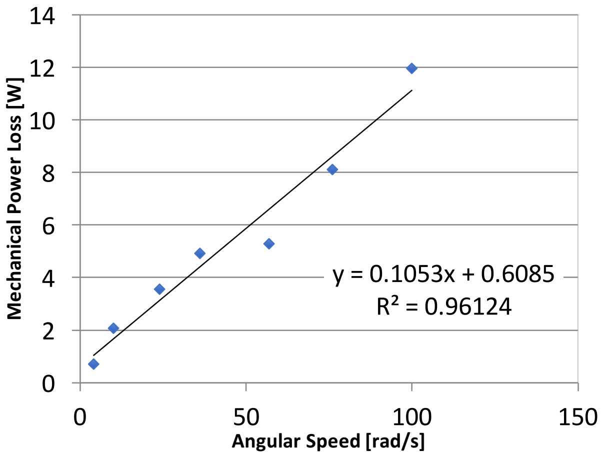


Fig. 8 Mechanical Power Losses

It can be observed that the mechanical power losses are linearly related to the angular velocity of the turbine. The input electrical power to the motor at each water flow rate as a function of the turbines angular speed is shown below in Fig. 9.

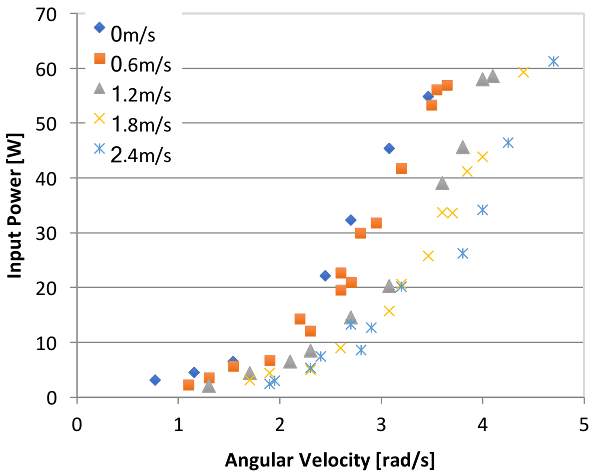


Fig. 9 Input Electrical Power to Motor

From this plot, the data corresponding to 0m/s water flow can be analyzed. Taking this data set and subtracting the mechanical and electrical losses, the plot shown in Fig. 10 can be obtained.

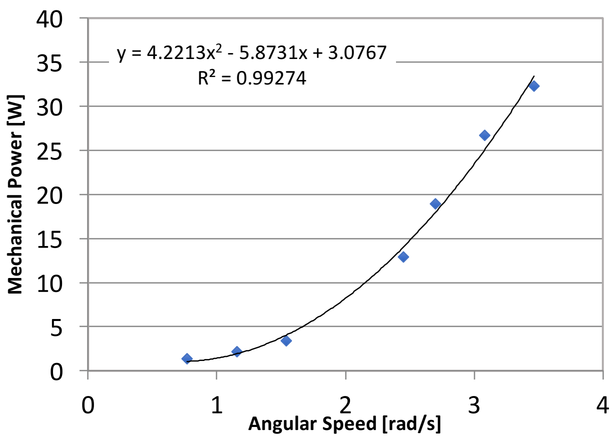


Fig. 10 Mechanical Power at No Flow

This plot demonstrates the amount of power required to spin the turbine in the water with no water flow. This is calculated from the following equation:

$$P_{no\,flow}(\omega) = [VI - I^2R - (\alpha + \beta\omega)] \qquad (2)$$

The regression equation from this plot will be used as the function $P_{no\,flow}(\omega)$ for the remaining datasets. From these datasets, the amount of mechanical power harvested by the turbine from the water flow can be found and is shown in Fig. 11 below.

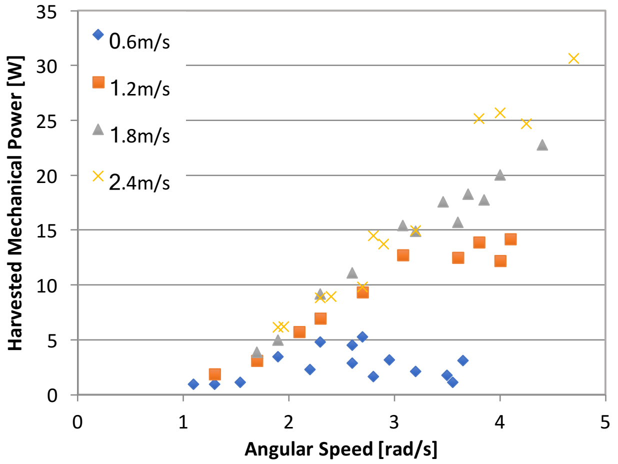


Fig. 11 Harvested Mechanical Power

From this, the Turbine efficiency vs. Tip-to-Speed ratio (TSR) can be plotted. The turbine efficiency is calculated as the ratio of the harvested power to the theoretical power available. The cross-sectional area of the turbine was 0.457m x 0.686m. Fig. 12 below represents the turbine efficiency vs. TSR.

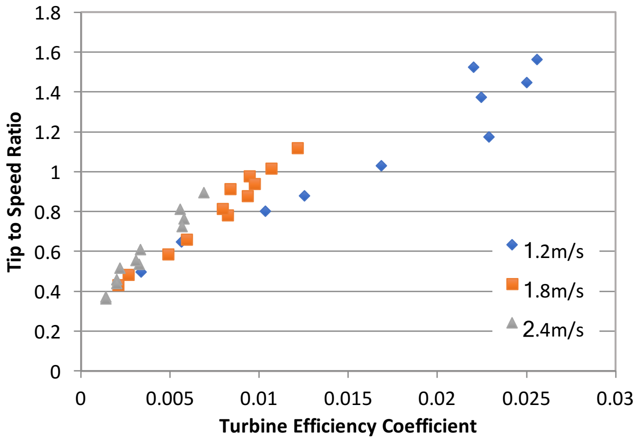


Fig. 12 Tip to Speed Ratio and Turbine Efficiency

These results coincided to a TSR ratio less than or equal to 1.6, which correlates to the lower range of data presented in [7] for a similar construction of turbine. It can be observed that the intersecting data correlates with both findings.

The Performance of the turbine can be observed in Fig. 11 and Fig. 12 above. The turbine assembly can be observed in Fig. 13. These results provide plots of the TSR versus the turbines efficiency. This efficiency is the C_k term in the power extraction equation of a tidal turbine. The datasets collected represent the turbine operating at a relatively low TSR. It can be observed in [7] that the upper end of this collected data correlates to the lower end of the data collected in [7]. This presented data corresponds to a C_k value of 0.026 for a TSR of 1.5. In [7] the C_k value is approximately 0.031 for a TSR of 1.5. This discrepancy could be accounted for in several ways. Error in the angle-of-attack angle, inhomogeneous water flow, error in the turbines vertical position, and the meshing surrounding the turbine disturbing the flow. In [7], a change of the angle-of-attack of 5 degrees resulted in approximately a 50% change in the C_k.

Fig. 13 Turbine Assembly

B. *Fish Behaviour*

During the 15 minute student observation, during the first week, sampling at the furthest point away from the turbine, it was found that the average time it took for the school of fish to pass the observation window was 15s in the morning, 12s in the afternoon, and 17s in the evening. In the second week, when the turbine was on, it was found that the fish did not school together and were no longer circling the tank. Due to this there was no sufficient time data during this week. During the third week, when the turbine was off, the average times were 17s in the morning, 14s in the afternoon, and 17s in the evening, see Table 1 below for a summary of these results.

It was noted that in the afternoon the fish were schooling much more tightly together than in the morning and evening when the turbine was off [3]. This result is interesting as it is unlikely this behaviour was related to feeding since feeding occurred at random times each day. It is possible that owing to increased noise levels in the tank area during the middle of the day because of increased human activity caused the fish to school tighter and swim quicker, as they would in the presence of predators [3]. A decrease in average lap time may indicate stress within the fish, and the amount of time schooling as well as the tightness of the school indicates stress. Defense against predation is one of the main advantages of schooling, when under stress by a predator the fish are likely to school tighter together and follow one another in escape maneuvers [3]. Other reasoning for schooling include navigation, communication, efficiency for travelling, and socializing [3]. An escape maneuvers or behaviour usually involves the fight or flight response and a burst or increase in swimming speed is observed [3].

When the turbine was on, the fish were either not all schooling when circling the tank, or swimming in a non-distinct pattern.

TABLE I
OBSERVATIONS FURTHEST POINT FROM THE TURBINE

Week	Turbine State	Avg. Morning Time [s]	Avg. Afternoon Time [s]	Avg. Evening Time [s]
1	OFF	15	12	17
2	ON	N/A	N/A	N/A
3	OFF	17	14	17

Table 2 below illustrates the average times it took for the school of fish to pass the observation window directly under the turbine for each of the three weeks. In the first week, when the turbine was off, the morning, afternoon, and evening averages were 8s, 5s, and 10s respectively. During visual observations by student(s) in week two, when the turbine was on, the fish were not observed to school together. During the first three days, the fish were circling the turbine cage and some individuals were circling the tank, or swimming in the tank with no distinct pattern, an interesting result that will be discussed in the next section. Therefore, no timing data of schooling behaviour was collected during the 15 minute visual observations conducted by student(s). Like the observations furthest point from the turbine, there is insufficient time data during week two when the turbine was on. After the first three days, most of the fish returned to circling the tank but not as a tight school, some individuals swam in random patterns. During week three, when the turbine was switched off, the morning, afternoon, and evening times were 10s, 6s, 13s respectively, see Table 2 below for a summary of results. During the third week, the fish returned to schooling tightly in the afternoon and circling the tank.

TABLE II
OBSERVATIONS CLOSEST TO THE TURBINE

Week	Turbine Switch	Avg. Morning Time [s]	Avg. Afternoon Time [s]	Avg. Evening Time [s]
1	OFF	8	5	10
2	ON	N/A	N/A	N/A
3	OFF	10	6	13

From the video recordings, during each week, the total amount of time spent schooling as well as the total amount of time engaged in other behaviours such as circling the turbine cage, swimming under the turbine, or swimming alone, was calculated. It was found that in the first week when the turbine was off, the fish spent 89% of the time schooling and 11% doing the other behaviour, see Fig. 14. During week two when the turbine was on, the fish spent 43.41% schooling and 56.59% engaging in the other behaviour, see Fig. 15. In Fig. 16 it is illustrated that during week three when the turbine was turned off, the fish spent 48.72% of the time schooling and 51.28% of the time engaging in other behaviour.

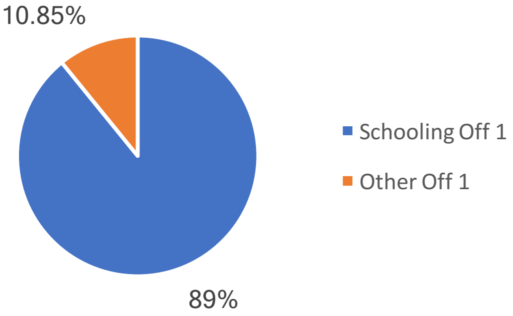


Fig. 14 Pie chart of the percentage of time analyzed by underwater video camera of Striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 89.15% of the time and other behaviour was 10.85% of the time.

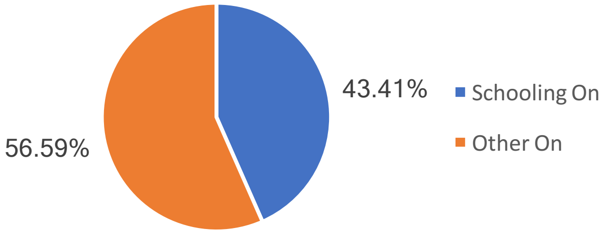


Fig. 15 Pie chart of the percentage of time analyzed by underwater video camera of Striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 43.41% of the time and other behaviour was 56.59% of the time.

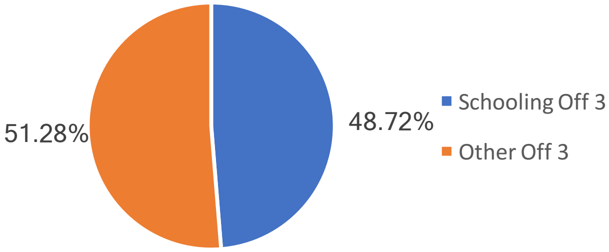


Fig. 16 Pie chart of the percentage of time analyzed by underwater video camera of Striped bass (*Morone saxatilis*) illustrating schooling behaviour or other behaviour. Other behaviours include swimming under turbine, alone, or circling turbine cage. Schooling behaviour was 48.72% of the time and other behaviour was 51.28% of the time.

Table 3 below presents the results of the paired t-tests. A significant difference was observed in the amount of time the fish spent schooling between week one (turbine off) and week two (turbine on). When the turbine was off, the fish spent 45.59% more-time schooling than when the turbine was running, see Table 3. However, the amount of time the fish spent schooling between week two (turbine on) and week three (turbine off) were similar, see Table 3.

Differences were also observed in ‘other’ behaviour between Week 1 and Week 2, see Table 3. No difference was observed for other behaviour between week two and week three, see Table 3.

While the difference in behaviour observed between week one and week two could be assumed to be because of the turbine, this does not answer why there was no difference between schooling and other behaviour observed between weeks two and three. We can only speculate that the turbine had ‘some’ influence, but whether this was a stress to the fish or something else is unknown. Further investigation is required to look at both physical (changes in noise, flow perturbations) and physiological (stress through cortisol) to understand the interactions of the fish with turbines in a controlled environment.

TABLE III
TEST OF CHOICE ANALYSIS

Test	Parameter 1	Parameter 2	P-value	Result
Paired t-test	Schooling Week 1 Off	Schooling Week 2 On	0.0397	Sig.
Paired t-test	Schooling Week 2 On	Schooling Week 3 Off	0.6512	Not Sig.
Paired t-test	Other, Week 1 Off	Other, Week 2 On	0.0395	Sig.
Paired t-test	Other, Week 2 On	Other, Week 3 Off	0.3143	Not Sig.

IV. CONCLUSION

This paper describes a multi institutional project. The goal of using the Aquatron facility as a lab space for animal-turbine interaction studies was achieved. The facility is well suited to the kinds of interaction studies that are needed and the only restrictions are in the size of the turbines or energy extraction systems that are installed in the tank. The turbine performed better than expected and the results correlated very well with the turbine results from previous tow tank testing [7]. There were many questions about how to design a test of value using fish and turbines as there are so many variables to consider (noise, flow, turbine depth, access to slower water, and more), fish swimming with/against the current or cross current flow, so the test was designed to give the team a starting point in this type of testing. The Aquatron Pool Tank was not designed for this purpose, but the modifications made have allowed the engineering and biology sides of tidal power to work in a controlled lab space and achieve valid and valuable results.

The initial tests indicate that there are many more questions to be answered with respect to the behaviour of fish around tidal turbines. Behaviour modifications were recorded and now the different aspects of the test that were observed can be explored individually in more detail. It is possible to test for longer periods of time, investigate habituation, investigate stress through cortisol testing, investigate noise impacts, investigate night versus day (turn out the lights and use a Didson camera), and investigate more restricted movement.

At this point it cannot yet be concluded that the fish modified their behavior due to the turbine alone and controlling for additional parameters will be critical in future testing. Future tests will likely be run without a netting around the turbine. It is anticipated that collaborations with a range of animal experts will enhance the understanding of animal interactions with marine renewable energy systems.

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